Exploring Dense Matter Physics with Neutron Star Observations

Les Rencontres de Noirmoutier 01/06/2026

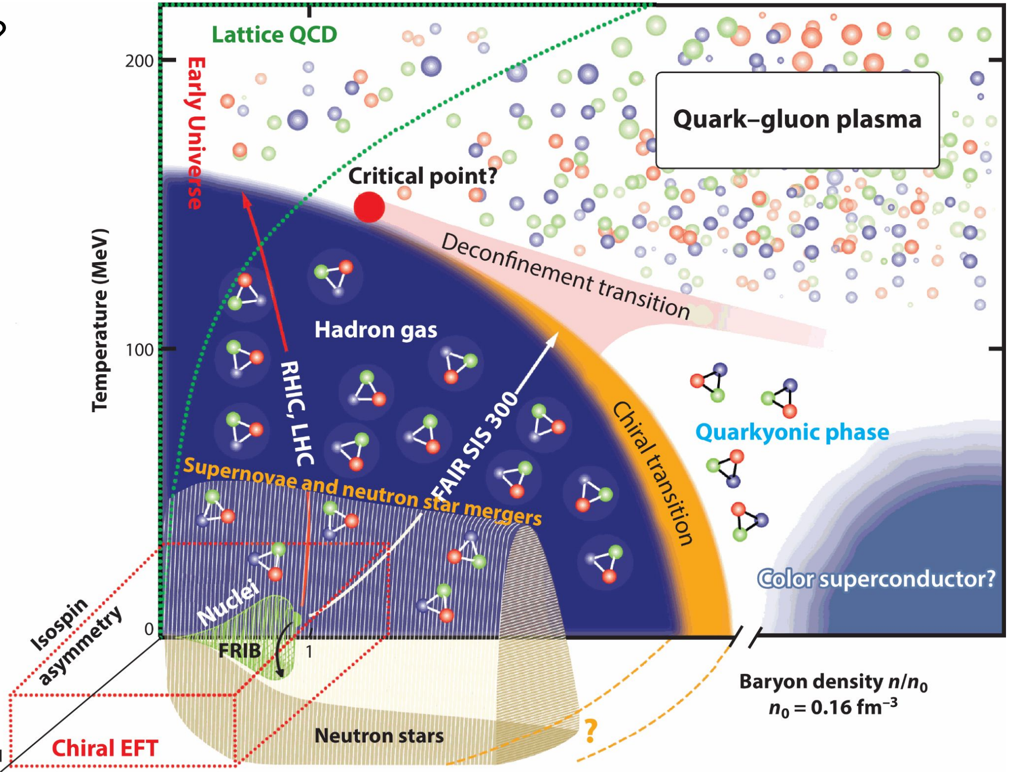
Lami Suleiman, Post-doctoral researcher

A limited understanding of dense matter properties

How well do we understand **strong interaction** ?

Parts of the phase Quantum ChromoDynamic diagram remains mysterious. Why ?

- **Theory**
  - **non-perturbative nature** of strong interaction
  - pQCD and chiral EFT
- **Experiments**
  - Facilities limited by thermodynamic conditions
  - Difficulties testing **isospin asymmetric** matter
  - Facility for Rare Isotope Beams



Drischler C, et al. 2021
Annu. Rev. Nucl. Part. Sci. 71:403–32

Matter with low T, high n, and high δ are found in **Neutron Stars** (NS) or NS-like matter.

Neutron Stars: the basics

Astrophysical objects of the **extreme**

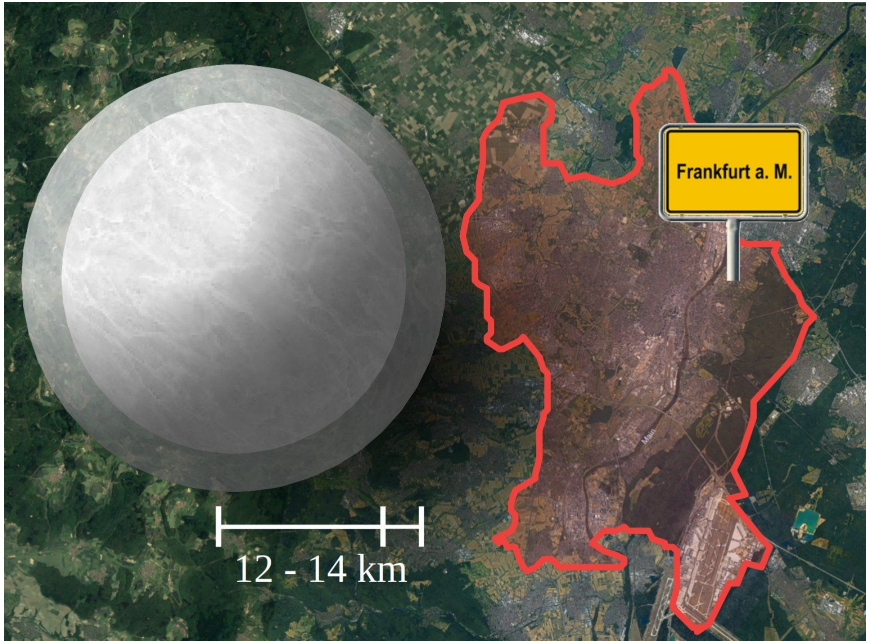
- Compactness M/R ~ 0.3
- Thermodynamic conditions
  - core reaching several n_0
  - zero-temperature approximation
  - NS-like matter: few tens of MeV
  - neutron rich = isospin asymmetry (N_Z - N_N)
- Extreme magnetic field: magnetars

Neutron star **structure in layers**

- Atmosphere (light elements)
- Crust : outer and inner crust
- Core: outer and inner core

Observations of NS parameters:

  - Mass, rotation frequency with radio
  - Mass-radius with x-ray
  - Mass-Tidal deformability with GW
  - Moment of inertia ? Soon ?



Credit: Lukas Weih, Goethe University

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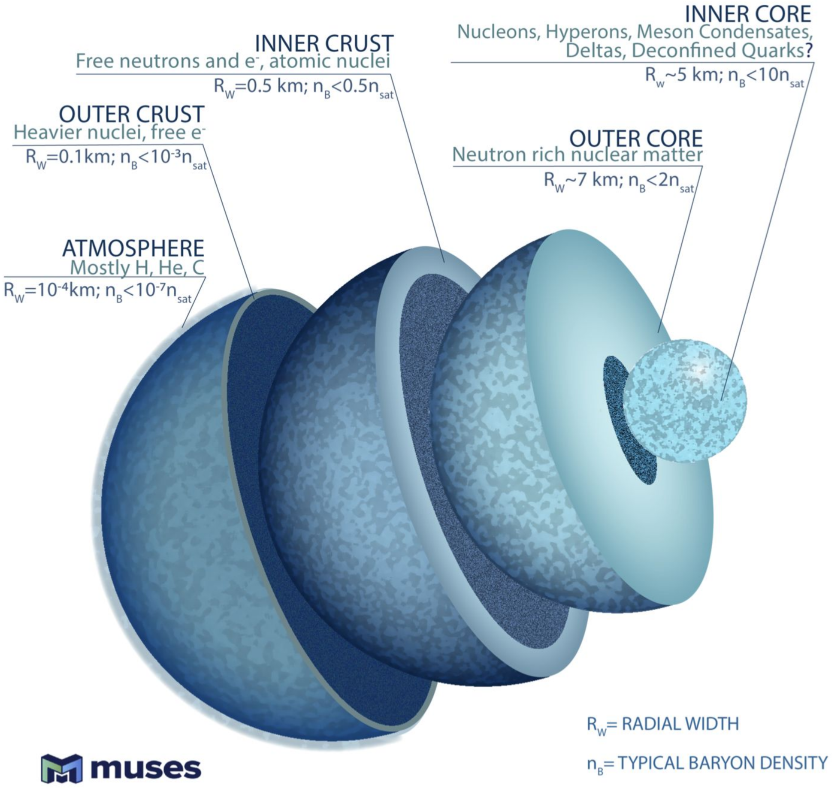

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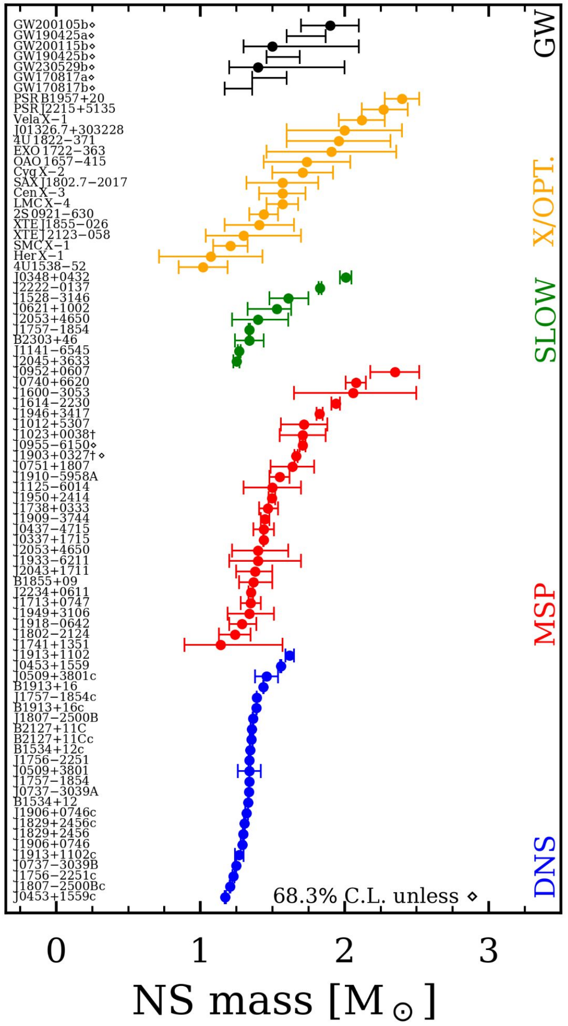

Figure adapted from Suleiman et al. 2021
Physical Review C

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X-ray Pulse Profile Modeling

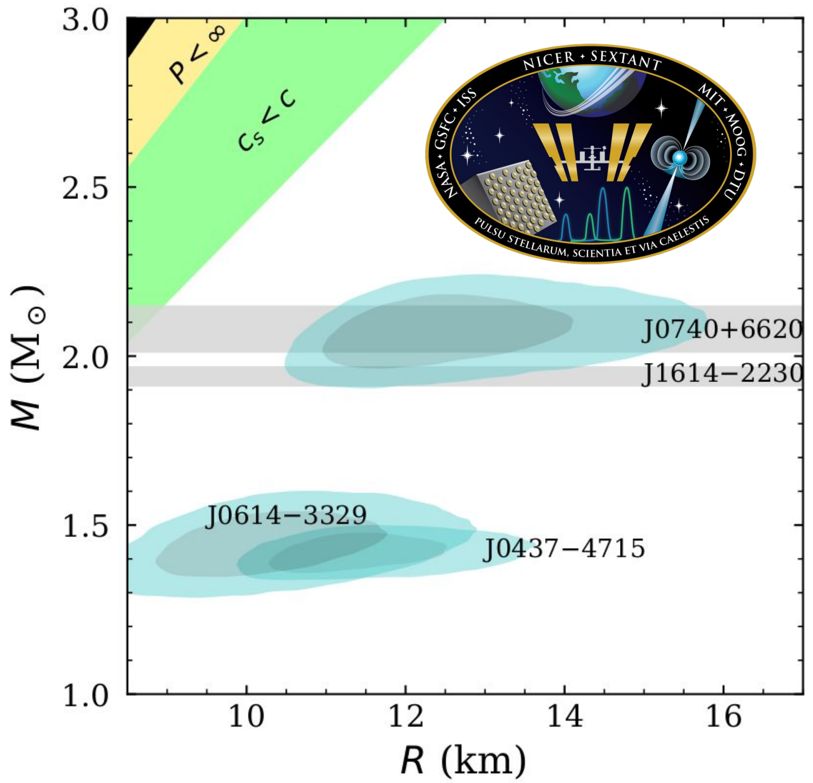

Figure adapted from MANITOU book

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From gravitational wave signal to extrinsic & intrinsic parameters

$$p(\theta|d) = \mathscr{L}(d|\theta)\pi(\theta) = \mathscr{N}\exp\left\{(d|h_\theta) - \frac{1}{2}(h_\theta|h_\theta)\right\}\pi(\theta)$$

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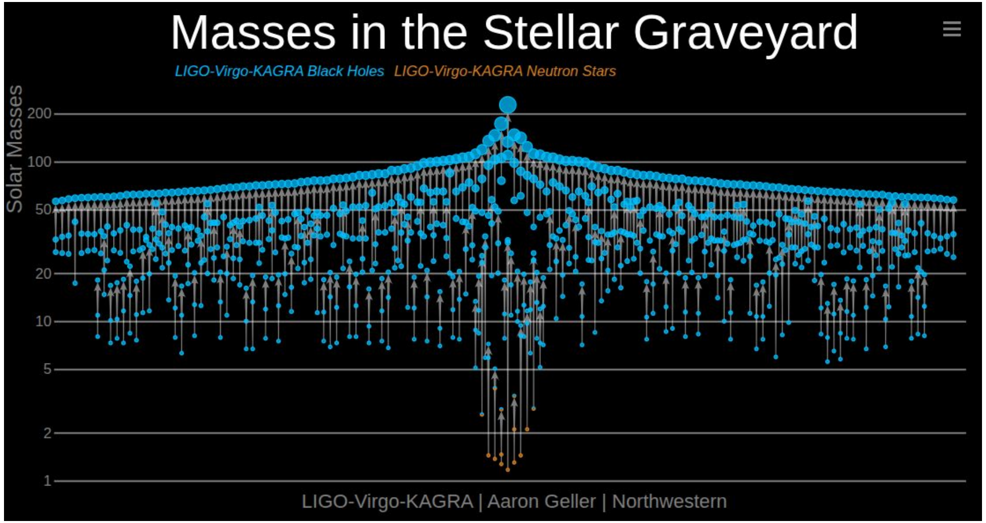

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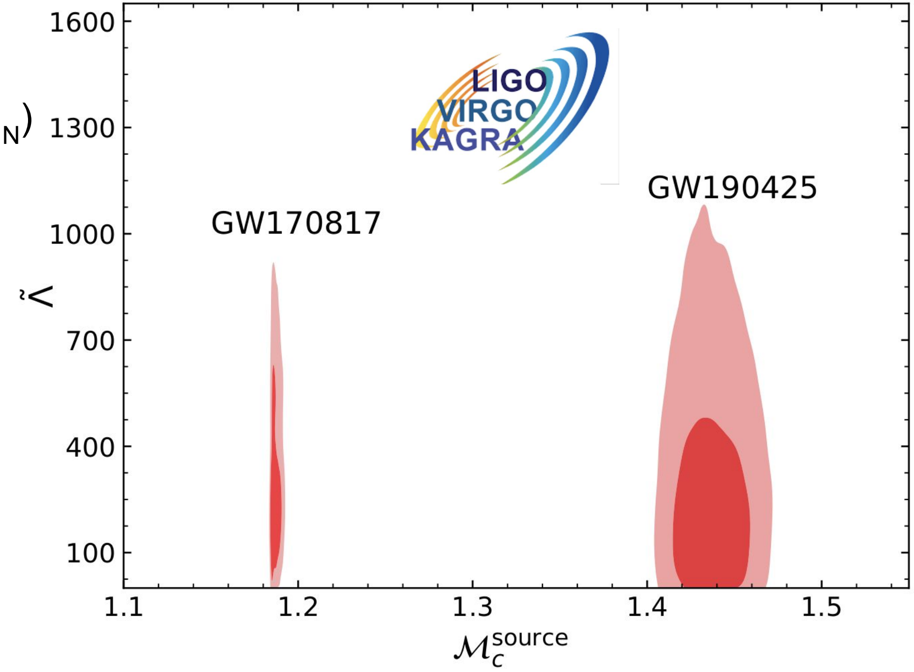

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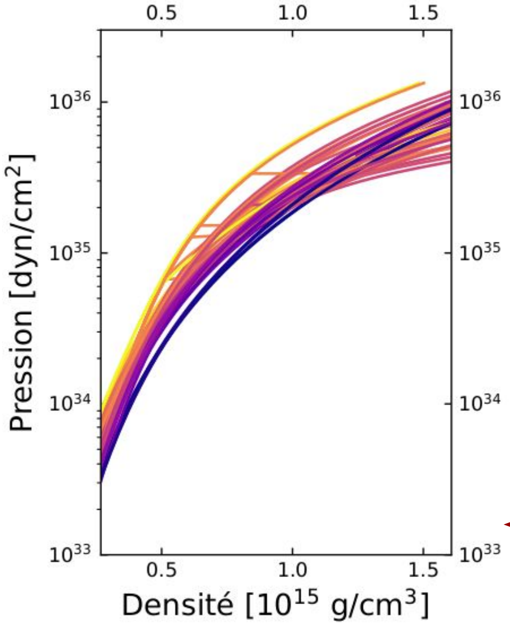
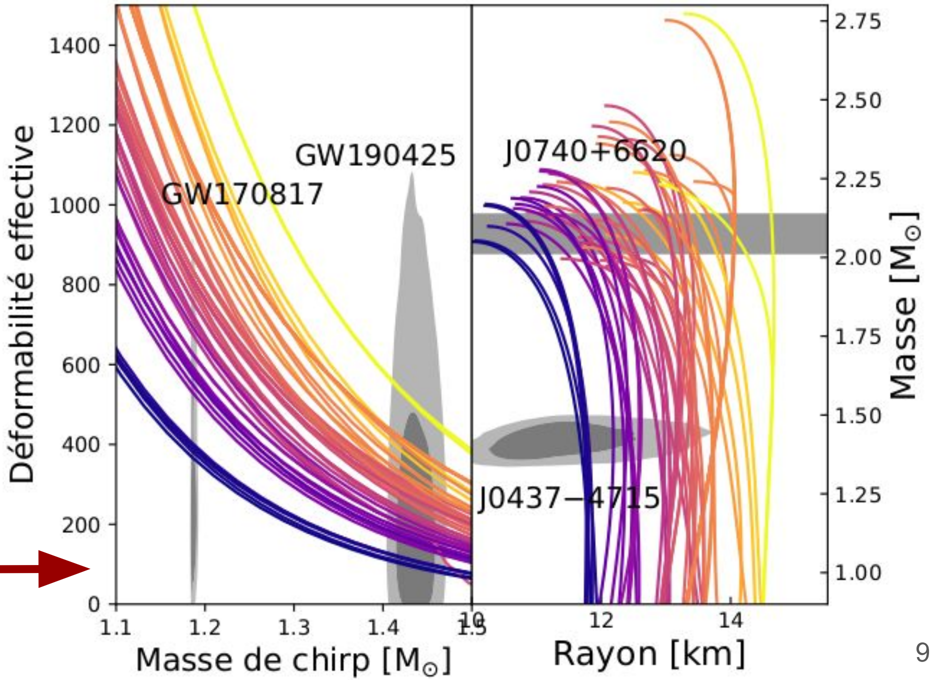
Equation of state inference

Equation of state (EoS) models for **inference**:

- EoS ↔M, R, Λ etc.
- Model selection: test EoS one by one
- Agnostic approach vs nuclear physics EoSs

Gravitation | Hydro | Thermo | Nuclear Physics





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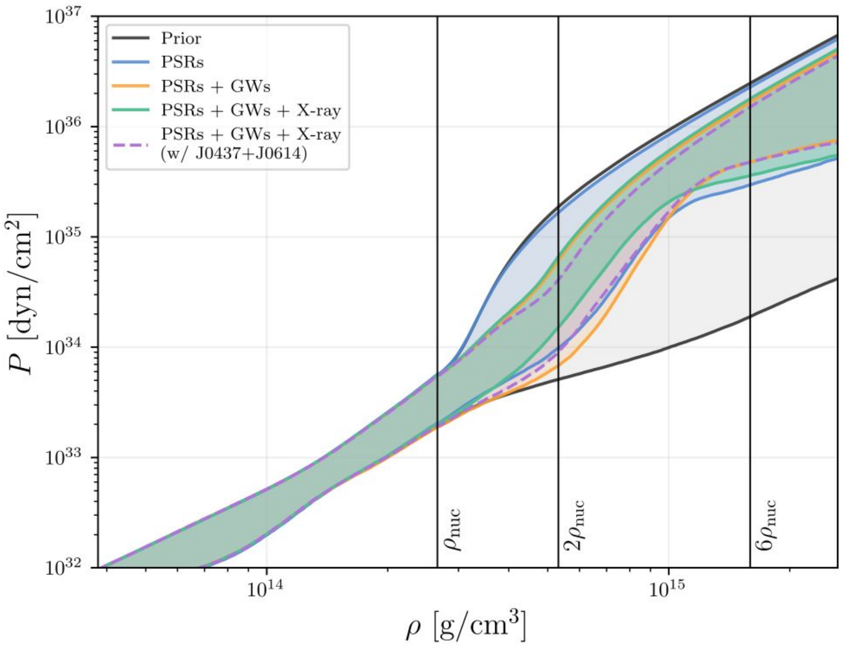
Semi-agnostic approach:

- **CUTER** Davis et al. 2024, Ng et al. 2025
- Combining with **nuclear information**
- Combining multiple **astrophysical information**

State of the art semi-agnostic models with Gaussian Processes



Ng et al 2025 Class. Quantum Grav. 42 205008

Future detections and prospects

Next few years:

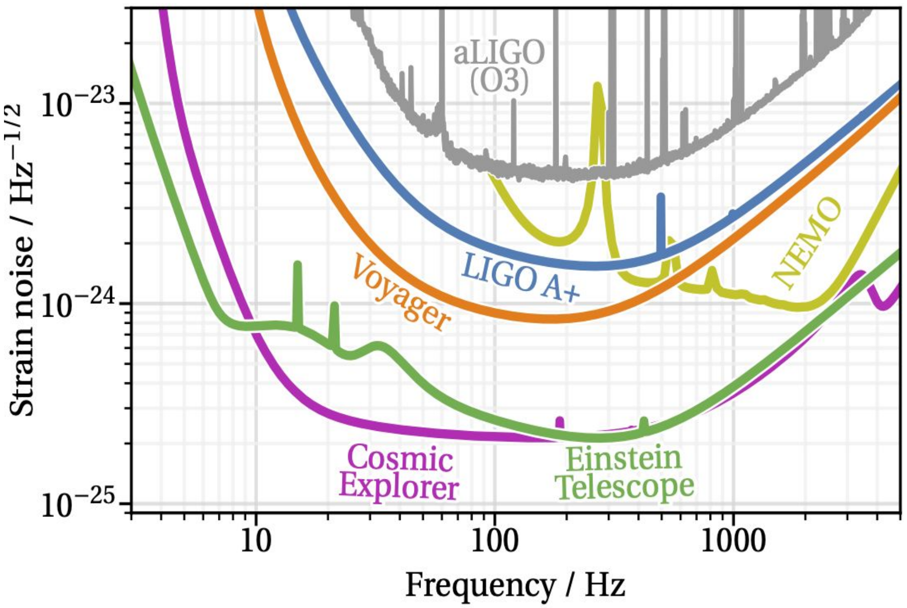
- SKA (radio)
- IR1 and O5
    - combined with electro spectrum
- NICER analysis

Next-generation of detectors

- Einstein Telescope and Cosmic Explorer
- NewATHENA
- Moment of inertia ?

Systematics vs. observational error:

- Reevaluate a number of approximations
    - quasi-universal relations
    - assumption for state of matter
    - waveform models etc.



https://cosmicexplorer.org/

post-merger data ?

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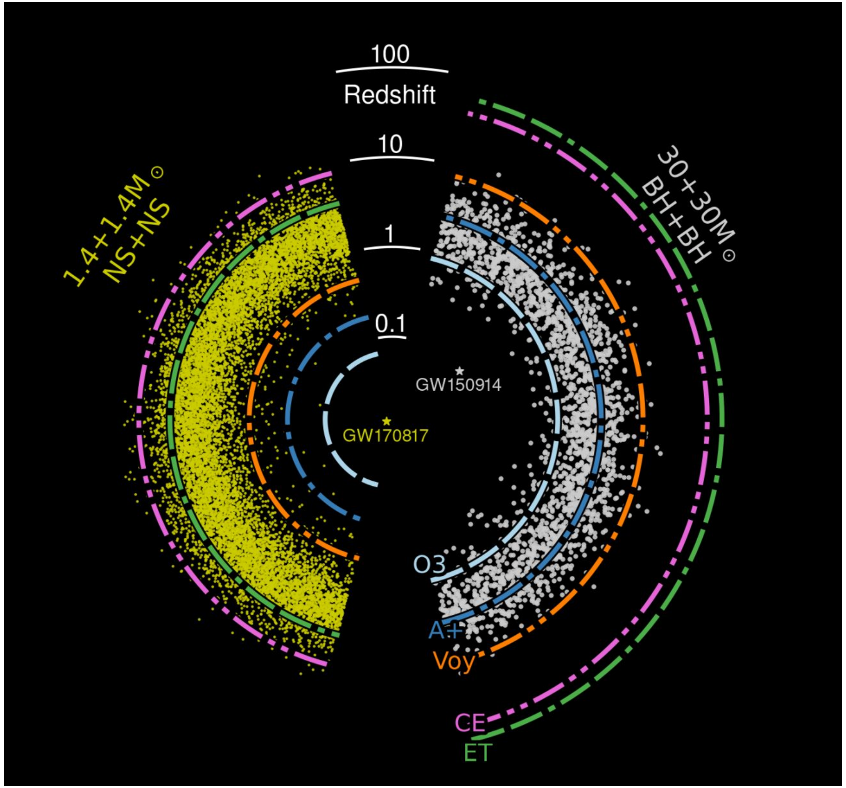

Credits: CE Science case

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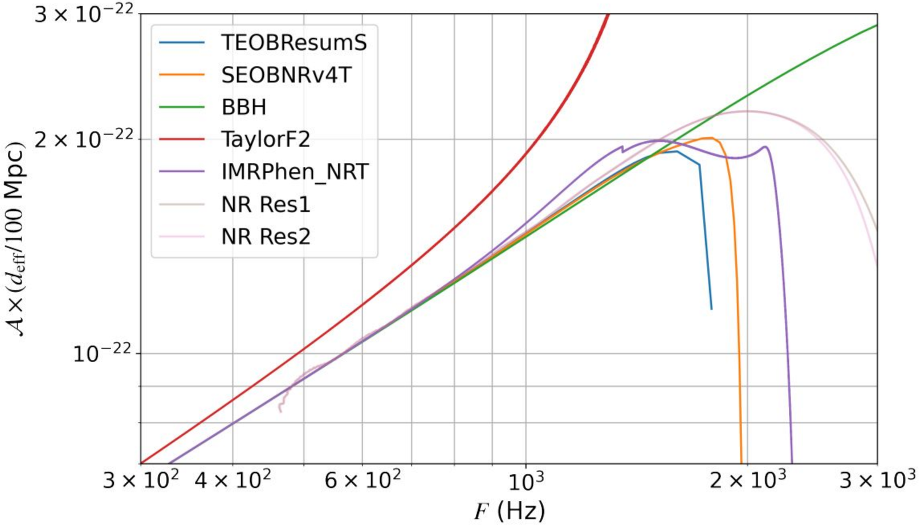
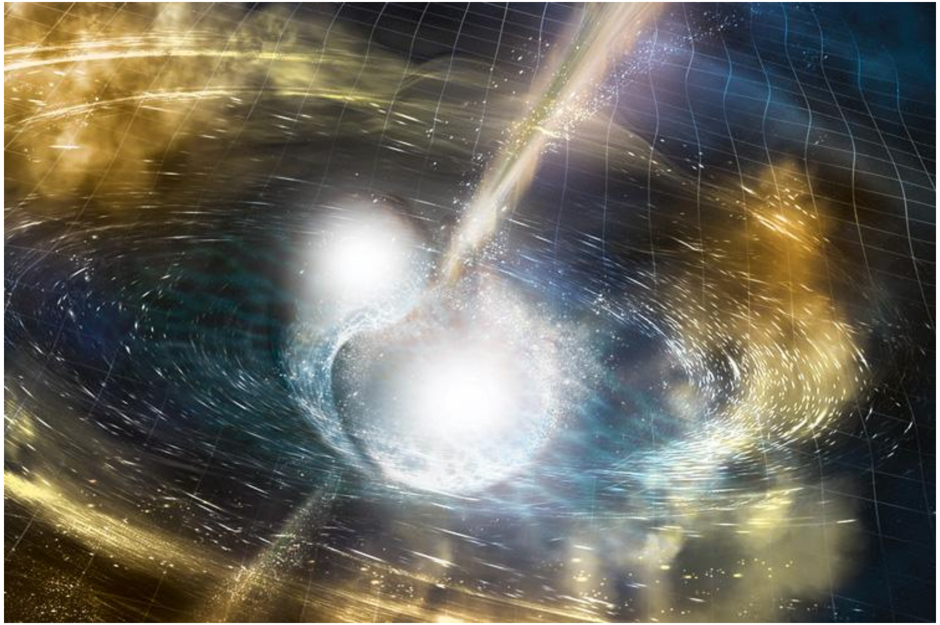
Read 2023, Class. Quantum Grav. 40 135002



Conclusion

- ➔ NS observables can probe dense matter physics beyond what can be achieved by nuclear theory and experiment
- ➔ Multi-wavelength, multi-messenger observations can be used
- ➔ Next-generation of detectors will provide more sources, more precise detections, but the community must prepare to analyse high-precision results



Credits Aurore Simonnet for Sonoma State University